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EFFICIENCY METRICS COMPUTING IN COMBINED SENSOR NETWORKS

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This paper discusses the computer-aided design of combined networks for offices and building automation systems based on diverse wired and wireless standards. The design requirements for these networks are often contradictory and have to consider performance, energy and cost efficiency together. For usual office communication, quality of service is more important. In the wireless sensor networks, the energy efficiency is a critical requirement to ensure their long life, to reduce maintenance costs and to increase reliability. The network optimization problem has been solved under considering of overall-costs as objective and quality of service including throughput, delay, packet losses etc. with energy efficiency as required constraints. This can be achieved by a combination of different planning methods like placement of wired and wireless nodes, tracing of cabling systems, energy-efficient sensor management and event-based sampling. A successful application of these methods requires a combined harmonized design at different levels of the networks. This paper aims to demonstrate how these methods are realized in the network planning. These tools provide optimized wired and wireless topologies under considering of costs, distances, transmitted power, frequencies, propagation environments and obstacles given in computer-aided design compatible formats.

Introduction

High-performance wired, wireless and mobile communication networks have become more and more important for global corporations, small and medium enterprises, public organizations and universities. The efficient and economic design of such networks, however, remains a challenge. Multiplicity of known design tools only provides a limited and hardly integrated support. Often the typical office LAN/WLAN are combined with building automation networks.

Computer-aided design of combined networks

CANDY (Computer Aided Network Design Utility) [1, 2] framework, a computer-aided design (CAD) tool-set for combined office communication and building automation networks based on diverse wired and wireless standards that discussed in this paper provides following features.

The framework supports the integrated design methodology providing a complete design workflow. It especially focuses on the combination of wired and wireless as well as wireless sensor networks design. The framework uses NDML, the dedicated Network Design Markup Language [1–7], a XML-based notation that serves as a uniform way of representing all major network elements (active and passive, including switches, routers, GW, patch fields, cross panels, base stations, sensors, access points as well as automation nodes), their detailed technical properties as well as their interconnections and

related configuration issues. In contrast to existing vendor-specific notations, NDML is based on open standards and enables interoperability and portability of network design projects.

CANDY is an open framework with a large set of design tools and functionalities. These include design editors, consistency checks, transformation tools, specific wireless network design tools, and integration of existing simulation environments. NDML serves as a common notation for these tools. CANDY framework uses established Java-based technologies to facilitate the tool development.

CANDY framework [1–7] has been conceived to provide an environment for creating and testing of new methods for networks design, including different aspects over a whole life cycle of a network. Fig. 1 demonstrates the plenty of the treated aspects such as performance analysis, energy and cost optimal placement as well as tracing methods implemented. Exact planning with satisfying of QoS (Quality of Service) and energy efficiency is necessary in order to build cost-effective and efficient wired and wireless networks. The CANDY framework consists of a number of tools intending to support and simplify network planning. The following modules belong to the framework: project manager; network editor; component browser; SCS trace router; wireless site finder; workload analyzer; bill reporter; front-end based on XML and NDML notations; loose-coupled and 3rd party tools, like, for instance, NS-2 [8–10]; component repository.

Compared to other tools, the advantages of CANDY framework are that it is easy to use, free-of-charge, open and extensible with new approaches, which can be implemented at any time as new modules.

We discuss the design of energy-efficient combined networks. Such networks include different technologies (for example wired and wireless connections with different communication protocols) and may be multipurpose (office or home intranet, industrial and home automation etc.). The approaches for gaining at different levels of the networks are recapitulated and the corresponding approach for their design is described.

Combined office and building automation networks

Building automation systems (BAS) implement the concept of a smart home, supporting traditionally HVAC (Heating, Ventilating and Air Conditioning) functionality as well as other comfort and security functions. They are realized as a distributed system of intelligent nodes (sensors, controllers, monitors, gateways). BAS are usually divided into three levels [11–13].

Field level, integrating sensors and controllers, uses a lot of proprietary protocols adapted to communication of short telegrams like measured values. The real-time requirements like small delays play an important role at this level.

At automation level, providing data communication between field nodes, fieldbus segments and management systems, the dedicated fieldbus systems (most prevalent are BACNet, KNX/EIB and LON) and centralized controls (different types of PLCs) have been established.

At management level supporting monitoring and management of the BAS, BACNet and OPC protocols as well as, at last time more and more important, Ethernet are used.

Traditionally, the BAS networks have been completely separated from other types of networks in a building. Since the beginning of 2000s, the BAS nodes support increasingly the access to Ethernet that allows re-using the available office networks and therefore reducing installation and maintenance costs for BAS networks. Another trend is an increasing role of wireless communication in office and BAS networks. Fig. 1 demonstrates a generalized deployment scenario of the network infrastructure by both BAS and office applications with wired and wireless communication technologies.

Possible variants of integration of building automation and office networks at different automation levels are as follows. Field level designates the sensor sampling and closed-loop control using Ethernet or WLAN. The applications have often strong real-time require-

ments. Automation level represents the integration and interoperability of heterogeneous fieldbus segments using Ethernet/IP-Gateways; use of IP-controllers and BAS-services over IP. Management level is the distant monitoring of BAS, facility management using web interface, e.g. for desktop PCs and PDAs.

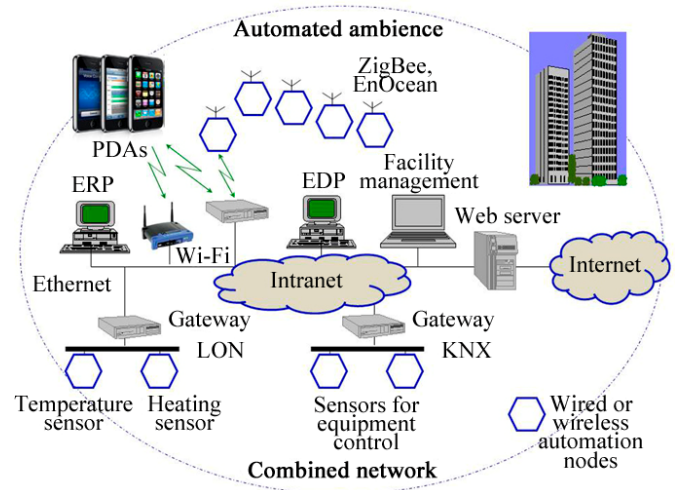


Fig. 1. Structure of a combined wired/wireless and office/automation system.

The trends mentioned above suggest that the designers of building automation and office networks would benefit from the combined design of their networks. At first, the design methods developed for office networks can be re-used for BAS. Secondly, the combined design would result in a better infrastructure, satisfying the requirements of both network types. Along with that, the combined design implies that the corresponding design tools support the different aspects of design as well as their mutual consideration. All these requirements are supported by an open architecture of CANDY framework, as it will be shown in next sections.

Combined network design within CANDY framework

The CANDY framework [1, 2] helps to solve complex optimization problems which appear during design of the IEEE networks based on structured cabling system (SCS) and the standards like DIN/ EN 50173 for physical constellation and tracing. The optimization problem can be formulated for the overall-costs (capital expenditures, CAPEX) under considering of constraints like data throughput, delay, jitter, packet losses and energy consumption [1–7]:

$$\min K(N, L, t) \wedge \max \text{QoS}(DR, \Delta, J, PL) \wedge \min(E) \quad (1)$$

where N is total number of deployed network devices; L denotes the total length of the infrastructure cabling

system (SCS); (DR, Δ, J, PL) designate the appropriately data rate, transfer delays, jitter and packet losses (PL) correspondingly (QoS parameters); t is the time factor. Also further parameters can be taken into account and used in the optimization. Along with that, the formulated optimization problem (1) has as a rule only quasi-optimal solutions due to its complexity [1].

One important distinguished feature of WSN regarding to the office typical LAN/WLAN is energy consumption optimization under QoS-considering. The tradeoffs should be considered during design to achieve the purpose of long-live reliable WSN with higher QoS, as well as availability and inter-operability of nodes. The stored energy density can vary between 10–50,000 $\mu\text{W}/\text{cm}^3$.

The estimation of the TTL integrated criterion can be made under considering of the following factors:

$$\max TTL = \alpha \partial q / \partial t(PTx, F, d, DR, SNR, TL, OH, \xi) \quad (2)$$

where q is the battery charge in Ah; F and PTx are transmission frequency and power; d denotes an average distance between SN (a hop distance); DR is SN data rate, TL designates an average telegram length; OH represents an overhead in the WSN telegrams; ξ is a centralized random value, distributed by Gauss; α denotes a logarithmic decrement factor.

Different planning tools of the CANDY Framework support the optimization task (1) for different technologies, comprising graph-based geometrical, queuing optimization, and event-driven simulation [1–10]. The CANDY tools are integrated with the aid of NDML, a special language as a glue, which provides interoperability with own self-developed tools (software components and modules) as well as with further (open) tools for design, verification and management of TCP/IP- wired and wireless networks. For instance, there are such well-known simulators and CAD systems as NetWorks, OPNET tools [9], AWE WinProp [10], NS-2, OM-NeT++, Verinec, Netopeer [1, 2].

Wireless sensor networks

The wireless sensor networks (WSN) [12–15] gained nowadays their maturity and play greater role year-by-year in industry manufacturing, intelligent buildings and monitoring of out-door areas (in health, agriculture, forestry, ecology and navigation) and so on.

The WSN are integrated together with communication networks LAN and WLAN as well as with proprietary networks like in home automation (KNX/EIB, LON) and industrial automation (CAN, Profibus), as shown in Fig. 1. This figure shows an automated ambience with a combined network.

A wireless sensor network consists of spatially distributed, autonomous sensor nodes (SN) to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, object motions or pollutions. The integration with communication networks LAN and WLAN in indoor scenarios via gateways (GW) offers a possibility of further measurement data processing with use of usual data access means like web interfaces and web services as well as middleware. The measurements can be also accessed by modern PDAs (WLAN, Bluetooth), e.g. an iPhone with installed specialized Apps or other smart phones with free Android OS Apps.

One of the most important problems of WSN is the energy efficient wireless sensor networking [12–15]. The energy efficient sensor nodes are intended to provide the autonomous long life as well as to reduce their maintenance costs and to increase reliability. Therefore, the software of wireless sensor nodes (OS, applications, and middleware like e.g. OSGi framework) should be very compact and energy-efficient. The tasks and the processed data have to be effectively scheduled and clustered. At the same time, the constructed WSN should fulfill the inter-operability and quality of service requirements.

The energy efficiency is also an issue in advanced sensor nodes when energy harvesting functionality should be rationally placed and optimal routes to the gateway are to be founded. The concepts of caching, threading and redundancy/replication have to be considered for minimization of energy consumption by SN — SN and SN — GW communication as well to increase the GW-performance.

Optimized methods for energy and cost efficient wireless sensor networks

The cross-layer approach combines the existing models, methods and tools in an integrated framework [1, 2, 7] and brings a large advantage due to leveraging of multiple tradeoffs between factors for energy consumption (Fig. 2). The important requirements on the design tradeoffs in energy efficient WSNs are listed below: efficient power sources of wireless nodes including long-live batteries or energy harvesting methods as well as power management mechanisms at physical level (PHY); efficient protocols (media access protocols, MAC) with reduced traffic and overhead; efficient operation systems and applications (APL), for example, the event-based approaches in WSN allow the effective use of power management mechanisms; optimized topology (cabling traces, placement, hierarchy, clustering) as well as redundant planning and functionality reservation.

The cross-layer design, also called harmonized design [5], considers these issues mutually. The security and networking layers are not considered in this paper, since they are very specific for different protocols and contribute less to the energy efficiency.

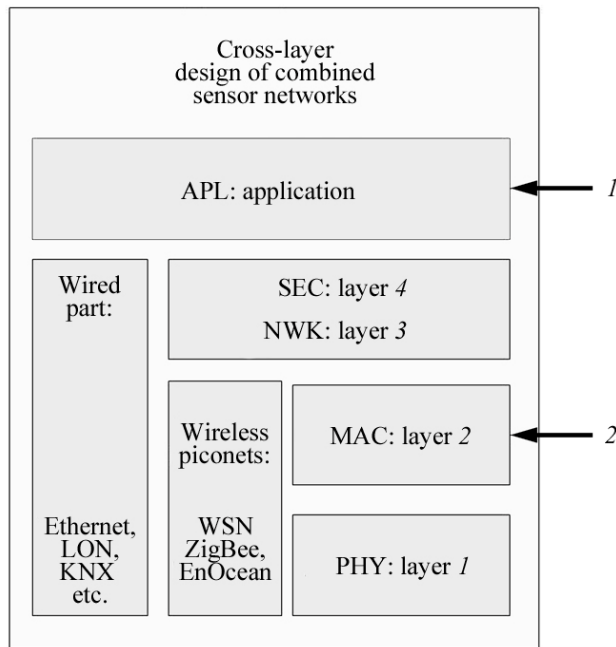


Fig. 2. Harmonized design of combined sensor networks at different levels and optimization methods: (1) Optimized component deployment, event-based sensor control; (2) Optimized sensor placement, optimized cabling system, energy harvesting.

In particular, the paper focuses on the following energy efficiency aspects of WSN: optimal placement of network elements (primary the wireless sensors) using specialized tools for wireless networks design; physical layer energy optimization by energy management and harvesting; event-based sampling and configuration of sensor nodes in WSN.

All these points are an important part of the concept of harmonized design for energy-efficient wireless sensor networks. We presume that the sensor nodes are already designed to support the energy efficiency in hardware (Fig. 3). The reason is that we concentrate on the network planners installers that already use the energy-optimized sensors from other vendors.

The depicted wireless sensor node uses the energy harvesting to increase its life time by absorption of the energy from the environment. At the WSN design phase (described below) an efficient wireless topology as well as sensor constellation regarding to the available alternative energy sources (sun light, vibration, radio smog) is to consider [12–22].

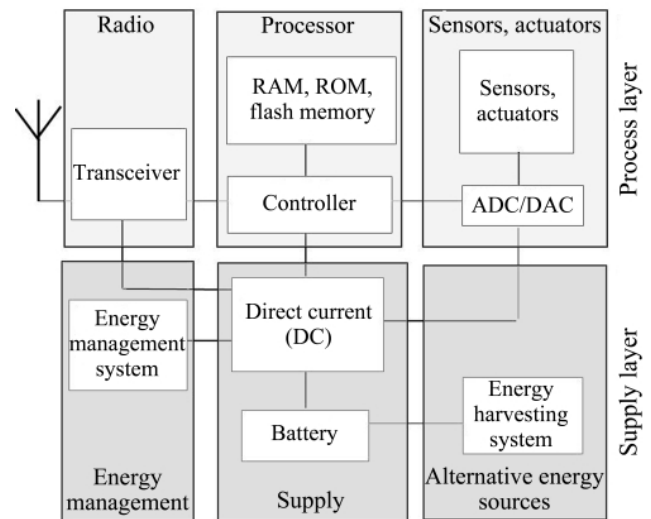


Fig. 3. Structure of a wireless sensor node: (ADC) analog-digital convertor; (DAC) digital-analog convertor.

Design of the optimized network

To solve the above mentioned tasks of network metrics optimization, the optimal component (products) placement and SCS tracing methods for combined networks are used. For these aims the following CAD tools should be deployed within CANDY framework [1–8].

CANDY wireless site finder (CSF) is the tool aimed to optimal wireless constellation taking into account the used frequencies, transmitted power and propagation environments (indoor or outdoor) and obstacles specified in CAD-conform formats. In particular, IFCXML format is used for exporting data from AutoCAD system.

CANDY trace router (CRT) is the tool for optimal automated tracing of the structured cabling systems within buildings with specification of server rooms (for switches, routers, GW, patch fields, cross panels) in CAD-compatible formats (e.g. IFCXML) based on the modified Dijkstra algorithm.

CANDY bill reporter (CBR) is the tool to automated cost computing based on the existing components and SCS tracing data as well as network products data bases.

The tool CANDY site finder (CSF) implements the multiplicity of models and algorithms for propagation computing for WLAN/WiMAX-nets as well as WSN combined design. The built-in propagation models and illumination algorithms for WLAN, WiMAX, WSN are classified regarding network technology, considered parameters, purpose areas (called as “category”) as well as propagation environments (indoor or outdoor) and their algorithmic complexity (expressed via Landau-symbol O). CSF realizes the following functions: import of AutoCAD, PythonCAD, NDML, IFCXML, PDF floor

plans, city maps, background images; export of XML, JPEG, BMP, PNG files; comfortable object management functions like adding, changing, and removing of objects; automatic placement of AP/BS/SN; computation and visualization of the following propagation models: Free Space Loss, Multi Wall, COST 231 Walfish Ikegami, Dominant Path Prediction, and Line of Sight; visualization of attenuation, receiving power, DR and coverage [1, 2, 8].

A parallelized run-time environment based on Web Services and the solutions for computation-intensive models for CANDY site finder are in work. A part of them (e. g. for DPP model) have been already implemented on the SGI Altix 4700 at ZIH@TUD (1024 dual-core Intel Itanium processors and 6.5 TB main memory) and discussed in [2, 7].

CANDY trace router (CTR) implements Dijkstra tracing algorithm belonging to the class of sub-optimal „greedy algorithms“ and calculates the shortest paths from the start node to all other nodes for the defined cable channels and coupling elements positions. The complexity of the algorithm is $O(n^2)$. The structured cabling systems length for LAN and the wired part of the combined network as well as the overall combined network costs are minimized [1, 2, 8].

The network design steps within the CANDY framework implement the following simplified workflow: import of building layout (geometrical data) from IFC/IFCXML format; switches, access points' constellation and SCS trace routing for LAN; design of hotspots (access points, wireless sensors) constellation; evaluation of network performance and costs as well as data export in NDML.

After a common analysis of the obtained design results the experts may consider the further interesting parameters of corresponding hotspots (e. g. wireless access points). Also, the export of these parameters can be used in other planning tools.

Event-based issues in WSN on the example of event-based control

The power management methods allow adjusting the computing power of the node and, correspondingly, its power consumption to the actual needs. This requires an appropriate event-based programming paradigm, which runs the applications only on occurring of proper external (e.g. wake-up signal or sensor value change) or internal (e.g. timers) events, reducing the number of redundant runs [16–22]. This paradigm is supported by modern operation system for WSNs, e.g. TinyOS or QNX. However, the energy-efficient design requires not only event-based implementation, but also realistic

evaluation of the event dynamics provided solely that the application dynamics (e.g. development of the observed signals) and its configuration are evaluated. The mentioned issue has been considered in this paper on the example of the event-based controls. To unify the possible configuration variants, an appropriate notation is described below.

The event based controls are a typical example of importance of considering the event-based issues, since they have a very diverse event dynamics that may depend on the properties of controlled lighting changes, principles of event generation as well as on the configuration of the automation nodes in the network. The dependence of event rates on the plant dynamics and principles of event generation for building automation have been considered in [19].

Along with dynamics, the configuration of nodes is essential, because the BAS control functions can be either distributed between different nodes or integrated in one node. The node configuration shows which types of data are transmitted over the networks. A brief notation is introduced below for a quick reference of the corresponding configurations of event-based controls, which combines the notation of loop elements and the connection configuration of the nodes. The notation is described as [16–22]:

$$I_x - S_{x-x} - C_{x-x-x-x} - A, \quad (3)$$

where I , S , C and A denote the loop elements, namely setpoint input device, sensor, controller and actuator; the letter x denotes the sampling variants, which can appear in the following sequence: ALi-ALs-CLs-PLc-ALc-CA-CLc; the hyphen “-” means that the loop elements are connected over the network, otherwise the loop elements are realized in the same node. If the sampling variant is irrelevant, it may be left unspecified (x).

The input device may be omitted in some situations, since it is mostly realized in an event-based way. However, the type of connection of the input device influences the communication delay between input device and controller. Different combinations are possible, as the examples in Fig. 4 demonstrate. Some combinations are not reasonable. For example, the configuration SP-AD-CAD-PID-I-A does not ensure that the control loop is closed at all moments of time [16–22].

The introduced generic model is intended to present the different implementation variants for event-based controls in an explicit and structured way. During design the engineer may use this model combined with theoretical approaches. At the end, the simulations can be employed as an appropriate instrument to validate the design (for example, see [16]). The classification of sampling elements is not complete and should be ex-

tended as far as new methods are developed. Also, investigation of new configurations created by combination of the sampling of the proposed general scheme may be reasonable. In other words, the proposed scheme can be used as a construction kit for further methods.

The configuration of node and estimation of the event dynamics based on BAS functions and plant dynamics are integrated (via a XML-front-end) in a CANDY BAS planning tool. The output data of this module are event rates that are produced in the network by BAS nodes. These event rates are used as input data for further network planning tools.

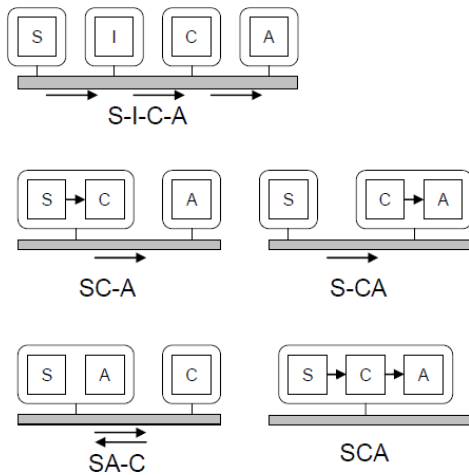


Fig. 4. Examples of node configurations.

Overall-cost analysis

Overall cost evaluation and forecast methods are supported via CANDY bill reporter that integrates the combined wired-wireless design by providing the cost overview of the whole network. It also supports the dynamic cost models that allow estimating the network value and its amortization over the whole life cycle. CBR's main idea is the optimization based on consideration of the total network costs as a generic optimization criterion with constraints on data rates and further QoS parameters. The tool has been validated on some practical examples.

CBR allows evaluating the objective cost functions $K(t)$ at specified time periods relative to the network installation moment. The general objective of the network optimization is minimization of the total costs in the long term:

$$K = K(N_1, N_2, DR, L, t), \quad (4)$$

where N_1 is an optimal number of deployed network devices (switches, routers); N_2 denotes a number of used hotspots (wireless access points or wireless sensor nodes) with optimized constellation for WLAN, WSN (radio wave propagation and energy issues are consid-

ered); DR is an appropriate network data rate; L is an optimized overall length of SCS. CBR uses the vector of constant parameters $(a, \alpha, \phi, \gamma, \eta, \theta, \mu, w, z)$ as settings to be adjusted [1, 2, 22]. The result of the tool is the list of the recommended network components along with the estimation of the overall costs as well as with the prognosis of their amortization.

The CBR tool together with the dynamic cost models offers a powerful instrument for the network designer to get the hints about long-term optimization of the networks. For company administration and house owners, the dynamic cost models provide estimating of the network value and comparing it with actual market situation. In the automation domain, the dynamic models allow to keep the QoS on the necessary level and to minimize the additional installation and operational costs.

CBR component repository has retrieving and updating functions to enable a comprehensive up-to-date database of network products and components with their market cost values. The project database includes the records about used components (PC, gateways, routers, switches, hubs, access points, cables, automation nodes etc.), media (coaxial cabling, UTP, STP, multi- and mono-mode fiber glass, plugs, patch panels and media converters), up-to-date installation and charges of internet service providers.

Conclusion

This paper discusses the computer-aided design of combined networks for offices and building automation systems based on diverse wired and wireless standards. Performance and cost efficiency are very important for the wired and wireless office communication LAN. Energy efficiency is a critical aspect for further deployment of WSN in mid-term. Its main objectives include long lifetime and reliable network with higher availability.

The design requirements on these networks are often contradictory and have to consider performance, energy and cost efficiency together. For usual office communication, quality of service is more important. In the wireless sensor networks, the energy efficiency is a critical requirement to ensure their long life, to reduce maintenance costs and to increase reliability. The network optimization problem has to be solved under considering of overall-costs (capital expenditures, CAPEX) as objective and quality of service (QoS, including throughput, delay, packet losses etc.) with energy efficiency as required constraints. This can be achieved by a combination of different planning methods like placement of wired and wireless nodes, tracing of cabling systems, energy-efficient sensor management and event-based

sampling. A successful application of these methods requires a combined harmonized design at different levels of the networks.

In the frame of the paper, the known methods for energy efficient use within WSN have been discussed. The combined approaches are demonstrated, which support cross-layer design of WSN together with LAN under considering of important trade-offs between multiple contradictory factors of efficiency.

This paper aims to demonstrate how these methods work and are realized in the network planning CANDY framework and, particularly, in tools CANDY wireless site finder, CANDY trace router and CANDY bill reporter. These tools provide optimized wired and wireless topologies under considering of costs, distances, transmitted power, frequencies, propagation environments (in-door/out-door) and obstacles given in CAD-compatible formats.

The relevant planning tools modeling SCS, signal propagation and costs have been discussed. The mentioned tools (CSF, CTR, CBR) are interfaced for design of optimal topology for LAN, WLAN and WSN under considering of geometry (IFCXML), ranges and frequencies, network products and costs (NDML), component constellation and energy issues, received power, propagation environments (in-/out-door) as well as obstacles.

A scenario for an in-door monitoring area (automated room) has been examined under use of cabling tracing tool CTR, wireless planning tool CSF and economy tool CBR.

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